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MAGNETIC SUSPENSION OPTIONS FOR SPACECRAFT INERTIA-WHEEL APPLICATIONS

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Listed below are the criteria that should be used when evaluating a suspension system for an inertia wheel in a spacecraft environment. The suspension must be compatible with a vacuum environment. It must exert minimal drag torques on the wheel and must consume only small amounts of power. The suspension must be capable of extended life with little or no attention. Additional functions that could be performed by the suspension include pointing the wheel's angular momentum vector to achieve active attitude control and precisely measuring the torques exerted on the wheel so that an attitude reference signal can be obtained.

DESIGN CRITERIA FOR SPACECRAFT INERTIA-WHEEL SUSPENSIONS

- VACUUM COMPATIBLE
- LOW LOSSES
  - DRAG
  - POWER CONSUMPTION
- LONG LIFE
- LOW MAINTENANCE
- HIGH RELIABILITY
- ANGULAR MOMENTUM VECTOR POINTING CAPABILITY (OPTIONAL)
- CALIBRATION CAPABILITY (OPTIONAL)

The primary advantage of utilizing a magnetic suspension for a spacecraft inertia-
eel application is the lack of physical contact between the rotor and the stator.
is leads to extended suspension life and reduced drag. The tolerances that must be
ld in construction of the suspension can be reduced from those required of other sus-
nsion system types such as precision ball and gas bearings. Reduced vibration and
ructural interaction can also be obtained. Since magnetic suspensions require no
bricant, they are quite compatible with a vacuum environment. Properly designed
gnetic suspensions also allow the functions of attitude control and attitude rate
nsing to be performed.

ADVANTAGES OF MAGNETIC SUSPENSIONS OVER OTHER SUSPENSION TYPES FOR SPACECRAFT INERTIA-WHEEL APPLICATIONS

- NO ROTOR/STATOR CONTACT
  - EXTENDED LIFE
  - REDUCED DRAG
  - REDUCED TOLERANCES
  - REDUCED MECHANICAL VIBRATION
  - REDUCED STRUCTURAL INTERACTIONS
- NO PROBLEM OF PROVIDING LUBRICATION IN A VACUUM
- POTENTIAL TO ELIMINATE MECHANICAL GIMBALS
- POTENTIAL FOR ESTIMATING SATELLITE RATES

A magnetic suspension system may perform one or more of the following functions: rotor support, torquing, and torque measurement. Regardless of function, the suspension design is typically driven by the inertia wheel precession torques, the stiffness of the surrounding structure, and by the angle through which the rotor must be tipped.

- FUNCTIONS PERFORMED BY MAGNETIC SUSPENSION
  - BEARING
  - TORQUER (OPTIONAL)
  - RATE SENSOR (OPTIONAL)
- FACTORS AFFECTING MAGNETIC BEARING DESIGN
  - WHEEL ANGULAR MOMENTUM
  - REQUIRED SLEW RATES OF SATELLITE
  - STRUCTURAL COMPLIANCES AND INTERACTIONS
  - MAXIMUM TILT ANGLE

There are four common designs for magnetic suspensions. The oldest type, the ssive dynamic field bearing (ref. 1), is stabilized by tuning circuit parameters for particular excitation frequency. This type typically consumes excessively high power r a spacecraft inertia-wheel application. Earnshaw's theorem states that a body in a atic magnetic field is stable in at most two axes. The stiffness along passively able axes is typically low. Many designers utilize active control of passively unable axes to achieve a stable system. Several advantages exist for actively controlable axes with servo control. These are addressed in detail on the next viewgraph.

MAGNETIC BEARING TYPES

TYPE	COMMENTS
PASSIVE DYNAMIC FIELD	• HIGH POWER CONSUMPTION
PASSIVE STATIC FIELD	• STABLE IN AT MOST TWO AXES (EARNSHAW's THEOREM) • LOW STIFFNESS
PASSIVE/ACTIVE	• UNSTABLE AXIS OF PASSIVE SYSTEM ELIMINATED WITH SERVO CONTROL
ACTIVE	• SERVO CONTROL REQUIRED • POTENTIAL FOR ADVANCED CONTROL STRATEGIES • POTENTIAL FOR ELIMINATION OF MECHANICAL GIMBALS

An actively controlled magnetic suspension will typically be much stiffer tha a passive suspension. The advantages of a high dc stiffness include more repeatable performance and reduced core losses due to changing flux in the rotor as it spins. Stiff suspensions are required if conventional electrical machines (such as inductio motors), which produce significant sideloading forces, are to be utilized.

Actively controlled magnetic suspensions may be used to provide set point con trol of the inertia wheel's angular momentum vector to provide attitude control with mechanical gimbals. By actively varying the damping of the suspension, performance near rotor critical speeds may be improved. Advanced control and estimation techniq aimed at suppressing whirl instabilities can also be applied.

ACTIVELY CONTROLLED MAGNETIC SUSPENSIONS

- HIGHER dc STIFFNESS THAN PASSIVE MAGNETIC SUSPENSIONS
  - MORE REPEATABLE PERFORMANCE
  - LOWER DRAG LOSSES
  - UTILIZATION OF CONVENTIONAL ELECTRICAL MACHINES POSSIBLE
- POTENTIAL FOR UTILIZING ADVANCED CONTROL STRATEGIES
  - SET POINT CONTROL OF ANGULAR MOMENTUM VECTOR
  - ACTIVE VARIATION OF DAMPING
  - WHIRL MODE SUPPRESSION

Magnetic suspensions exert forces either through the attraction of a ferromagnetic body or by the Lorentz force.

Ferromagnetic attraction type magnetic suspensions can be further classified by the manner through which the magnetic field is produced. Purely electro-magnetic suspensions have very low gain near zero current and are highly non-linear. Permanent magnet biased electromagnets, however, possess relatively high gain near zero current and are more nearly linear.

Magnetic suspensions that produce forces by the Lorentz force across a fixed length air gap have an advantage in terms of core loss since the core material sees a constant flux. Lorentz force suspensions are very nearly linear. By utilizing a permanent magnet rather than a wound core to produce the magnetic field, copper losses are reduced.

ACTIVE MAGNETIC BEARING DESIGNS

- FERROMAGNETIC ATTRACTION
  - PURE ELECTROMAGNET
    - LOW GAIN
    - NON-LINEAR
  - PERMANENT MAGNET (PM) BIASED ELECTROMAGNETS
    - HIGH GAIN
    - LINEAR
- LORENTZ FORCE
  - FIXED GAP LENGTH
    - ELIMINATES CORE LOSSES
    - LINEAR
  - PERMANENT MAGNET FIELD
    - REDUCES COPPER LOSSES

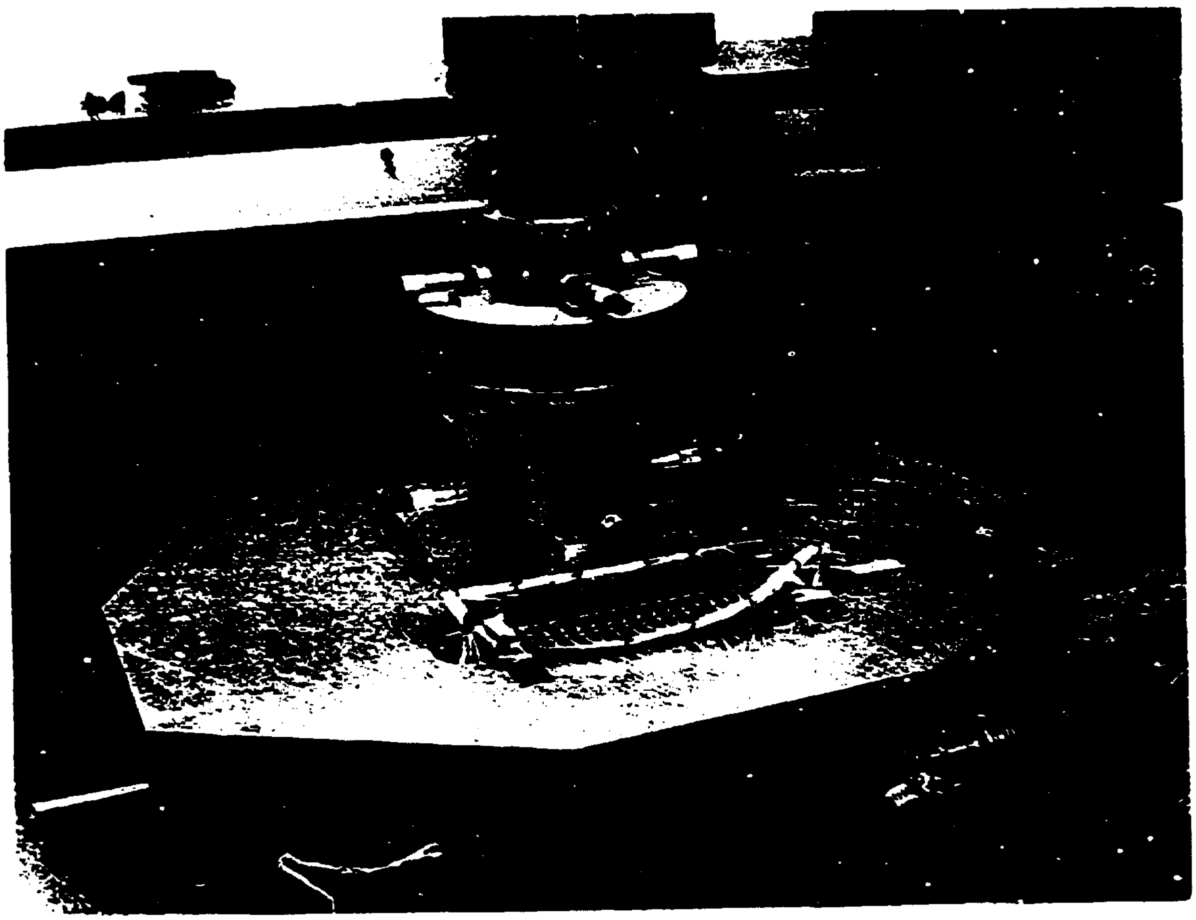
The Charles Stark Draper Laboratory (CSDL) has been involved in magnetic suspension technology for more than 30 years. The definitive reference on float suspensions was written by three CSDL engineers in 1974 (ref. 1). A 5-axis actively controlled flywheel suspension supporting a 12 lb rotor was constructed in 1978 (refs. 2, 3, 4). A magnetic suspension system for removing all but a nominal preload from the ball bearing support of a 200 lb flywheel was constructed in 1981.

There are currently three advanced magnetic suspension programs at CSDL. A single axis actively controlled magnetic vibration-isolator and a magnetically suspended inertial reference unit are being constructed and tested. A study of a Combined Attitude, Reference, and Energy Storage (CARES) system (ref. 5) is also in progress. The goal of this study is to demonstrate the feasibility of performing the energy storage, attitude control, and attitude reference functions of a satellite with high energy density, magnetically suspended inertia wheels. A novel Lorentz force type magnetic suspension is being constructed and tested as part of this program.

DRAPER LAB MAGNETIC SUSPENSION EXPERIENCE

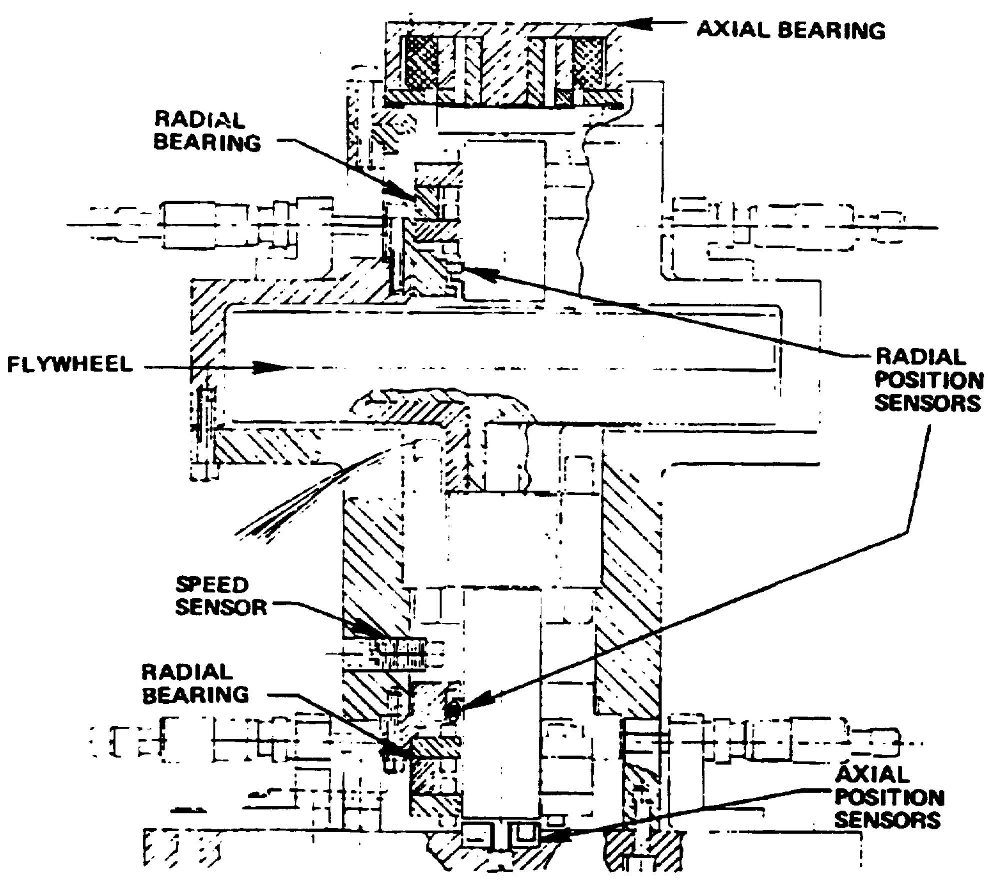
- FLOAT SUSPENSIONS
- 5 AXIS ACTIVELY CONTROLLED FLYWHEEL SUSPENSION (12 lb WHEEL)
- HYBRID FLYWHEEL SUSPENSION (200 lb WHEEL)
- PRECISION ACTIVE MAGNETIC VIBRATION ISOLATION
- MAGNETICALLY SUSPENDED INERTIAL REFERENCE UNIT
- COMBINED ATTITUDE, REFERENCE, AND ENERGY STORAGE (CARES) SYSTEM

As an example of a typical flywheel magnetic suspension, the 5-axis actively controlled flywheel shown here will be discussed.

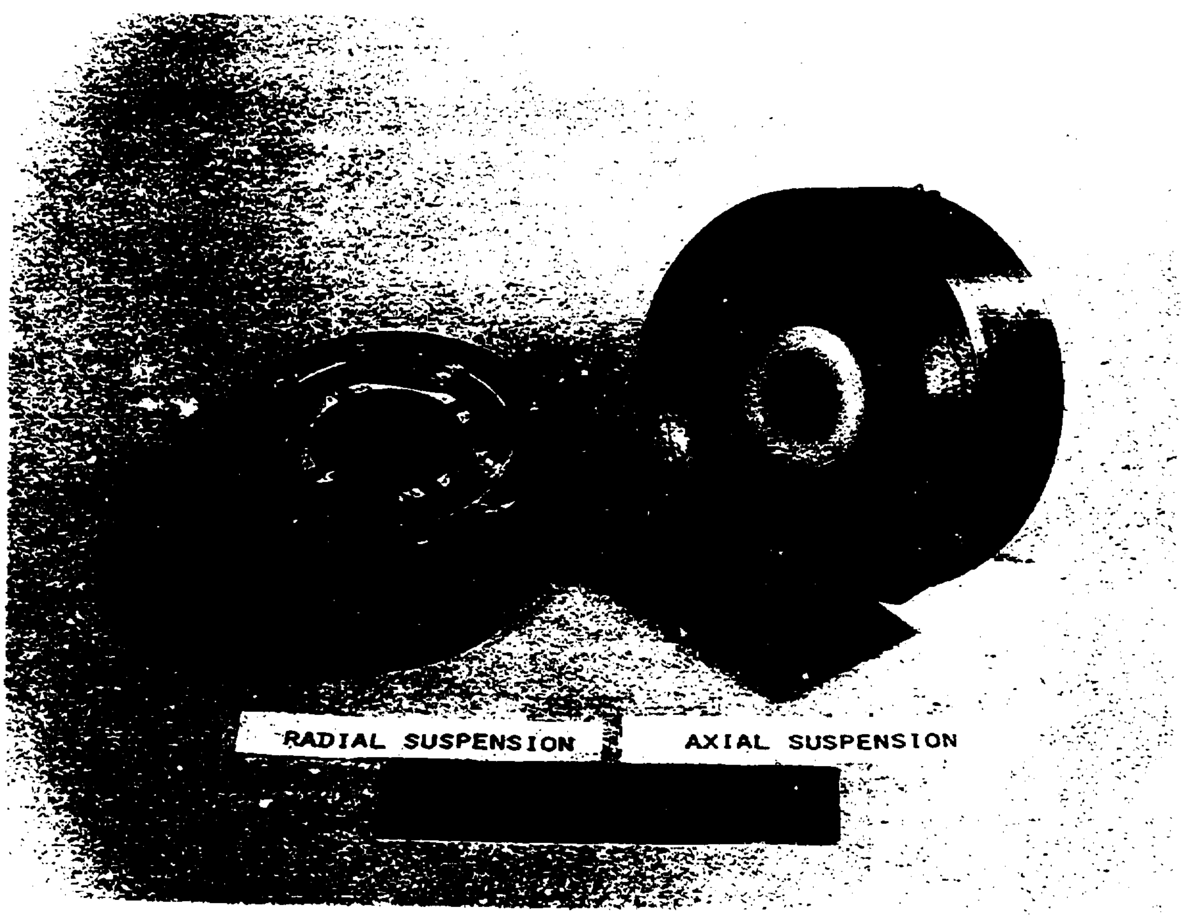


The figure below shows the internal arrangement of components. This system uses three actively controlled bearing elements, two radial and one axial, to control five degrees of freedom. Three inductive position sensors and an optical speed sensor are also used.

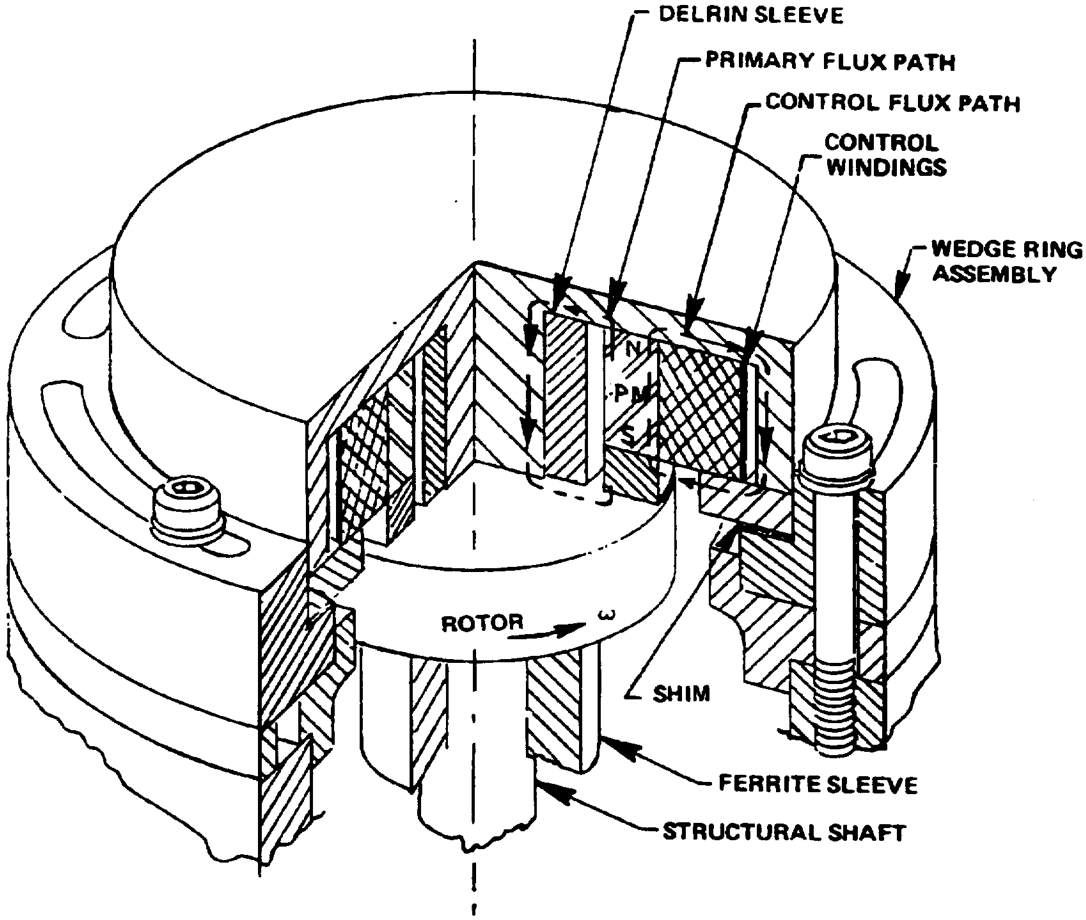
The flywheel module was designed to have a vertical spin axis so that the suspension that supported the weight of the wheel would not see changing fluxes due to rotor eccentricity and thereby reduce losses.



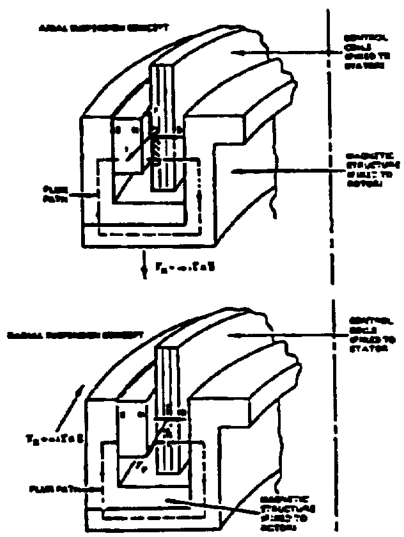
The photograph below shows the magnetic actuators that were used in the 5-axis actively controlled flywheel. Each is a permanent magnet biased electromagnet which uses a permanent magnet to produce a biasing field and control coils to obtain active control.



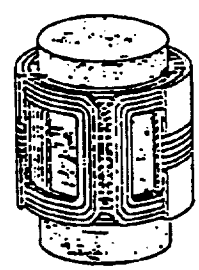
As an example of the operation of a permanent magnet biased magnetic suspension, consider the axial bearing of the 5-axis actively controlled flywheel that is shown below. The primary flux for suspension is provided by an axially oriented permanent magnet. Control of the air gap flux is obtained by using a control coil to shunt flux through an alternate flux path that has been provided in the magnet housing.



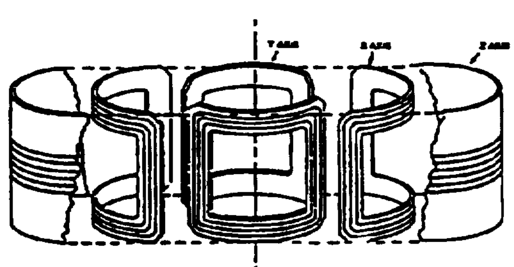
The CARES system magnetic bearing is shown below. Forces are exerted on the flywheel due to the interaction of rotating permanent magnets and stationary control coils. The figure also shows the winding configuration required to produce these forces. The windings of the control coil structure are shown assembled and in exploded form.



CARES MAGNETIC SUSPENSION CONCEPT



CONTROL COILS ASSEMBLED



CONTROL COILS DETAILED

Proper material selection in terms of either permanent magnets or core materials is critical to a successful magnetic suspension design.

When selecting a permanent magnet, maximum energy product is of primary importance since this directly affects the magnet size. The proper mix of remanence and coercivity must also be considered to make a small cross sectional area or long air gap design work. The relative ease with which a permanent magnet can be machined should also be considered.

Core materials are typically selected on the basis of their core loss characteristics (as measured by their hysteresis loop and volume resistivity) but ease of magnetization must also be considered. Ease of magnetization is measured by a material's permeability (one of three types, depending on application). Operating a core material in its saturation region is typically wasteful of power.

MATERIAL CONSIDERATIONS

- PERMANENT MAGNETS
  - MAXIMUM ENERGY PRODUCT
  - PERMANENT FLUX DENSITY
  - COERCIVE FORCE
  - MACHINABILITY
- CORE MATERIALS
  - HYSTERESIS LOOP
  - RESISTIVITY
  - PERMEABILITY
    - INITIAL
    - MAXIMUM
    - INCREMENTAL
  - SATURATION FLUX DENSITY

It is safe to conclude that the basic technology required to utilize an actively itrolled magnetic suspension system in a spacecraft inertia wheel has been satis-torily demonstrated, and that the design and control experience necessary to produce is hardware is available.

In addition, there is currently in progress a great deal of effort aimed at im-oving magnetic materials. These advances are taking place in the areas of high energy oduct rare earth/cobalt magnets and low loss ferroceramic core materials. These ad-ices are certain to facilitate magnetic suspension design.

CONCLUSIONS

- THE BASIC TECHNOLOGY REQUIRED FOR MAGNETIC SUSPENSION OF A SPACECRAFT INERTIA WHEEL EXISTS:
  - – SUSPENSION DESIGN EXPERIENCE
  - – CONTROL TECHNOLOGY
- RECENT ADVANCES IN MAGNETIC MATERIALS FACIL-ITATE MAGNETIC SUSPENSION DESIGN

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